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Aggregate Disintegration and Wettability for Long-Term Management Systems in the Northern Appalachians

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Assessment of the structural properties of discrete soil aggregates is fundamental to understanding soil erosional processes. Management-induced changes in soil organic carbon (SOC) concentration may significantly alter aggregate properties. The disintegration and wetting characteristics of individual aggregates and their relationships with SOC concentrations were determined for a Rayne silt loam (fine-loamy, mixed, mesic Typic Hapludult) under long-term (>22 yr) moldboard plow (MP), no-till with (NTm) and without manure (NT), pasture, and forest systems in the northern Appalachian region. Aggregate disintegration was assessed based on the kinetic energy (KE) of simulated raindrops required to detach 1- to 8-mm aggregates at −0.01, −0.1, −1, and −154 MPa soil water potentials. Management affected aggregate resistance to the erosive energy of raindrops ($P < 0.01$). Aggregates from forest soils required the highest KE (>5.0 μJ) for disintegration and those from MP soils the lowest (<1.9 μJ). At the −0.01 MPa potential, the KE needed to disintegrate aggregates in NTm was about three times higher than for NT, indicating that manure addition improved aggregate stability. Aggregates from cropland had very low water repellency, but those from forest management have some water repellency. Aggregate disintegration was correlated with measured soil erosion in which MP required the lowest raindrop KE to produce the highest runoff and soil loss. The SOC concentration explained 48% of the variability in aggregate disintegration and 86% in aggregate wetting. Long-term management altered aggregate disintegration, but its effects on aggregate wetting within agricultural practices were small.

Abbreviations: KE, kinetic energy; MP, moldboard plow; NTm, no-till with manure; NT, no-till without manure; PTF, pedotransfer function; ρ_{agg}, aggregate density; SOC, soil organic carbon; SOM, soil organic matter; TS, tensile strength; WDPT, water drop penetration time.

Quantitative assessment of soil structural stability at the aggregate level is fundamental to understanding the macroscale structural attributes of the whole soil (Kay, 1998). Aggregate structural properties such as strength, sorptivity, and wettability control soil erodibility (Eynard et al., 2004; Legout et al., 2005) and SOC dynamics (Blanco-Canqui et al., 2005) and can be valuable indicators of soil response to management. In well-aggregated soils, surface aggregate attributes are of key interest in understanding and modeling soil erosional processes. Most researchers have used large samples (i.e., group of aggregates or bulk soil) for assessing soil stability (Nimmo and Perkins, 2002) and erodibility (Lal, 1994) rather than single structural units or aggregates (Mbagwu and Bazzoffi, 1998; Munkholm and Kay, 2002). Mechanisms of soil erosion such as detachment by rainfall may be better understood by assessing the stability of single aggregates. Techniques such as wet sieving involve submergence and oscillation of a group of aggregates (Nimmo and Perkins, 2002) and thus are not suitable to study the stability of an individual aggregate (Loch and Foley, 1994). Moreover, determination of stability of a group of aggregates, based on Stokes' law, assumes that all aggregates are homogeneous, isotropic, and have a uniform density and deformation (Hillel, 1998), overlooking the heterogeneity of field aggregates. McCalla (1944) pioneered the design of a simple raindrop technique to quantify the stability of individual aggregates of a silty clay loam, and Bruce-Okine and Lal (1975) used a similar technique to establish a soil erodibility index for tropical soils. Recent studies along these lines to quantify aggregate disintegration are few, but are needed to understand management impacts on soil erosional processes (Eynard et al., 2004; Legout et al., 2005).

Soil detachment by rainfall largely depends on the ability of surface aggregates to resist the disruptive energy of raindrops (Bruce-Okine and Lal, 1975). The aggregate resistance to raindrops is influenced by soil organic matter (SOM), which stabilizes aggregates by binding soil particles through physical and chemical processes (Tisdall and Oades, 1982) and, in some soils, decreasing the wettability and rate of water entry into the aggregate (Letey, 1969; Chenu et al., 2000; Eynard et al., 2004; Goebel et al., 2005). The composition of the SOM and the type of organic binding agents influence the stabilization and hydrophobicity of aggregates. The main binding agents are classified as transient (e.g., polysaccharides), temporary (e.g., roots and fungal hyphae), and persistent (e.g., polymers) (Tisdall and Oades, 1982). The SOM-derived products such as humic and aliphatic substances (Chenu

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et al., 2000) and waxes (Ellerbrock et al., 2005) can impart hydrophobic properties to the aggregates, slowing their wetting, disintegration, and slaking, and thus moderating soil erosion. The effects of long-term (>20 yr) MP and NT systems on the wettability of discrete aggregates are not well understood. In some soils, management may change not only SOC pools, but also the hydrophobicity of SOM (Capriel, 1997). While MP and NT soils are generally assumed to be hydrophilic (Wallis and Horne, 1992), they may exhibit some water repellency depending on the duration of management, manure application, management-induced changes in the quantity and quality of SOM, and the soil type. Indeed, Hallett et al. (2001) reported for a silt loam that aggregates from NT soils were 43% more water repellent than those from MP soils. Conversely, Eynard et al. (2004) showed that aggregates from NT and MP soils were all "wettable" for different soil types, including loam, silt loam, silty clay loam, silty clay, and clay. Ellerbrock et al. (2005) observed that wettability increased with increases in SOC concentration up to 10 g kg^{-1} and then decreased rapidly with further increases in SOC concentration. Chenu et al. (2000) and Eynard et al. (2004) reported that aggregates from forest and pasture soils had slower wettability than those from cultivated soils.

Previous studies suggest the strong need to further clarify the effects of long-term tillage management on aggregate wetting and disintegration in response to changes in SOC concentration. Silt loam soils in the northern Appalachians in Ohio on steep slopes (>10%) are widely used for agricultural production but are highly prone to erosion (Rhoton et al., 2002). Long-term tillage management practices in this region can significantly change SOC concentrations in soil aggregates (Blanco-Canqui et al., 2005), but the effects of these changes in SOC concentrations on disintegration and the wetting rate of individual soil aggregates have not been well elucidated. Blanco-Canqui et al. (2005) reported significant differences in SOC concentration in <8-mm-diam. aggregates among NTm, NT, chisel plow, disk, pasture, and forest soils in the northern Appalachians. For the same soils, Shukla et al. (2003) observed that the mean weight diameter of aggregates under long-term NTm (3.8 mm) and pasture (3.4 mm) management was significantly higher than under NT (2.1 mm) and MP (1.1 mm), indicating that land use and tillage management strongly influenced the stability and size distribution of aggregates. While soil structural stability has been widely studied, the dynamic properties of individual aggregates such as wettability and disintegration by raindrop impact under long-term management systems have not been extensively quantified. The long-term (>35 yr) NT management systems at the USDA North Appalachian Experimental Watershed (NAEW) in Coshocton County, Ohio, provide a unique opportunity to assess the interrelationships among microscale aggregate structural properties under soils with the same texture, slope, and mineralogy, but different management.

Our objectives were to: (i) determine aggregate disintegration and wetting of individual aggregates for a Rayne silt loam for long-term MP, NT, NTm, pasture, and forest in the northern Appalachian region of Ohio, and (ii) assess relationships among aggregate disintegration, SOC concentration, soil erosion rates, and related physical properties of aggregates. The hypotheses tested were that aggregate disintegration is: (i) affected significantly by management practices due to changes in SOC concentration, (ii) a sensitive indicator of soil erosion potential, and (iii) can be estimated from other soil properties using pedotransfer functions (PTFs).

MATERIALS AND METHODS

Description of the Study Site and Experimental Watersheds

This study was conducted at the NAEW in the spring of 2005. The NAEW (40°16′19″ N and 81°51′35″ W), established in the late 1930s, is one of the pioneering watershed research stations in the USA and comprises about 400 ha of uplands intermixed with narrow and steep valleys. Cropping and tillage systems at the NAEW are practiced on undulating slopes (∼12% slope), portraying the typical farming practices in the region. Five neighboring watersheds under long-term (>22 yr) MP, NT with beef cattle manure (NTm), NT without manure, pasture, and forest were selected for this study. The cultivated watersheds were small (<1 ha), while the two watersheds under forest and pasture were relatively large (>1 ha). All watersheds have undulating slopes (>10%) except the one under the MP treatment (0.2% slope), which was a small plot (0.12 ha) sited on the summit position of a pastured watershed. The MP, NT, and NTm plots were managed under continuous corn (*Zea mays* L.). Orchardgrass (*Dactylis glomerata* L.) was the dominant species in the pasture watershed, and white oak (*Quercus alba* L.) and red oak (*Quercus rubra* L.) were the most common trees in the forested watershed. Management details for each watershed are given in Table 1. The dominant soil for the five watersheds is Rayne silt loam, containing 209 g kg^{-1} sand, 638 g kg^{-1} silt and 153 g kg^{-1} clay. The soils are deep, well drained, unglaciated, and have four well-defined horizons (A, B, C, and R) developed from sedimentary rocks including coarse-grained sandstone, shale, and some limestone (Kelley et al., 1975).

Soil Sampling and Analyses

Bulk soil samples (∼1 kg) were collected from three sampling locations 3 m apart within the summit position of each watershed in May 2005 before corn was planted or the MP watershed was tilled. Samples were obtained from 0- to 10-, 10- to 20-, and 20- to 30-cm depth intervals. The three sampling locations were used as pseudoreplicates as the

Table 1. Management history of the five watersheds including moldboard plow (MP), no-till (NT), no-till with manure (NTm), pasture, and forest management at the North Appalachian Experimental Watershed in Coshocton, OH.

Treatment	Management history
MP	22 yr continuous corn, moldboard plowed to 0.25 m deep, disked twice, and harrowed before planting; 150 kg N ha^{-1} applied as NH_4NO_3.
NT	35 yr continuous corn, 150 kg N ha^{-1} applied as NH_4NO_3, and herbicides applied for controlling weeds.
NTm	41 yr continuous corn, manured with beef cattle manure each spring at 15 Mg ha^{-1}, 150 kg N ha^{-1} applied as NH_4NO_3, and herbicides applied for controlling weeds.
Pasture	Perennial orchardgrass (>50 yr).
Forest	Perennial hardwood forest (white and red oak; >100 yr).

watersheds are not replicated. Samples were air dried at 20°C for 72 h, gently crushed, and sieved through a nest of sieves to obtain 1- to 2-, 2- to 4-, 4- to 6-, and 6- to 8-mm-diam. aggregates for the determination of disintegration and wettability. The aggregate disintegration was determined using a raindrop simulator based on the design by Bruce-Okine and Lal (1975) and Al-durrah and Bradford (1981). It consisted of a Mariotte bottle connected to a 50-mL burette installed at 3-m height to form raindrops 4.8 ± 0.02 mm in diameter and 0.12 ± 0.03 g in weight with a terminal velocity of 3.5 ± 0.1 m s^{-1}. The simulated raindrop fell through a 3-m-long and 0.20-m-diam. transparent polyvinyl chloride tube to reduce drop drift and ensure that the drop struck the same spot on each aggregate placed on a 0.5-mm-mesh sieve. The aggregates for the disintegration test were equilibrated to −0.01, −0.1, −1, and −154 MPa soil water potentials. Aggregates at −0.01, −0.1, and −1 MPa potentials were equilibrated using a combination of tension table and pressure plate extractors (Dane and Hopmans, 2002), while the pressure potential of −154 MPa corresponding to air-dry aggregates was calculated based on the constant temperature of 20°C and a relative humidity of 32% (Munkholm and Kay, 2002) using

$$\text{Pressure potential} = RT/M \ln(p/p_0) = -154111 \text{ J kg}^{-1} = -154 \text{ MPa} \quad [1]$$

where R is the molar gas (air) constant (J mol^{-1} K^{-1}, T is the temperature (K), M is the molar mass of gas (mol), p is the pressure potential (kPa) at T, and p_0 is pressure (kPa) at the reference temperature. The ratio of pressures (p/p_0) is equal to the relative humidity. The water in the Mariotte bottle was at 23 ± 0.2°C during the measurements. The number of simulated raindrops required to disintegrate an individual aggregate was recorded and converted to kinetic energy from the mass and terminal velocity. The determination of aggregate disintegration was conducted only for the 0- to 10-cm soil depth.

The water drop penentration time (WDPT) method was used to determine the wettability of 6- to 8-mm air-dry aggregates for the 0- to 10-, 10- to 20-, and 20- to 30-cm depth intervals (Letey, 1969). This involved placing drops of deionized water (23°C) on top of discrete aggregates using a microsyringe and recording the time (in seconds) required for the drop to completely penetrate the aggregate. Wettability was classified as: wettable or non-water-repellent (WDPT < 1 s), very low repellency (1 < WDPT < 10 s), and low repellency (10 < WDPT < 60 s) (King, 1981).

Runoff and Soil Loss Data

Data on soil loss and runoff collected from the same watersheds by Rhoton et al. (2002) and Jacinthe et al. (2004) were used to study their correlations with the raindrop KE measured in this study. Data for the long-term MP and NT watersheds were obtained from Rhoton et al. (2002), who measured runoff and soil losses in spring before corn planting from 6.01 by 0.76 m replicated plots within each watershed using a multiple-intensity rainfall simulator (Meyer and Harmon, 1979) that rained at 50 mm h^{-1} for 1 h. Data for the pasture and forest watersheds were obtained from Jacinthe et al. (2004), who collected runoff and sediment samples under natural rainfall for one entire year from these two watersheds, which are equipped with rain gauges, runoff volume recorders, and Coshocton wheel runoff and sediment samplers (Bonta, 2002).

Data on Soil Organic Carbon Concentration and Aggregate Physical Properties

Data on aggregate disintegration and WDPT measured in this study were correlated to aggregate properties such as SOC concentration, aggregate bulk density (ρ_{agg}), and tensile strength (TS) reported in a companion study by Blanco-Canqui et al. (2005) for the same watersheds. Aggregates were ground and sieved through 0.25-mm sieve for the determination of SOC concentration by the dry combustion method (900°C) using a CN analyzer (Vario Max, Elementar Americas, Hanau, Germany; Nelson and Sommers, 1996). The ρ_{agg} was measured by the clod method (Grossman and Reinsch, 2002). Each aggregate was weighed, coated with Saran resin, immersed in distilled water at 20°C, and weighed again to determine its weight loss. The TS of the aggregates was determined using the crushing method (Dexter and Watts, 2001). The TS of air-dry aggregates was measured at a soil water potential of about −160 MPa based on the constant room temperature of 22°C and 33% relative humidity (Munkholm and Kay, 2002).

Statistical Analysis

A split-split-plot design with management as the main factor, aggregate size as the subplot, and water potential as the sub-subplot was used to test whether differences in the KE of raindrops required to rupture aggregates were significant. Data on KE were lognormally distributed; consequently, statistical analyses were conducted on log-transformed data. Because of significant treatment × aggregate size × soil water potential interactions, treatment effects were further assessed by aggregate size and water potential using a one-factor ANOVA model. Differences in WDPT among treatments were analyzed by soil depth using a one-factor ANOVA model. Stepwise multiple regressions were used to develop PTFs for aggregate disintegration. All statistical analyses were conducted using the SAS statistical

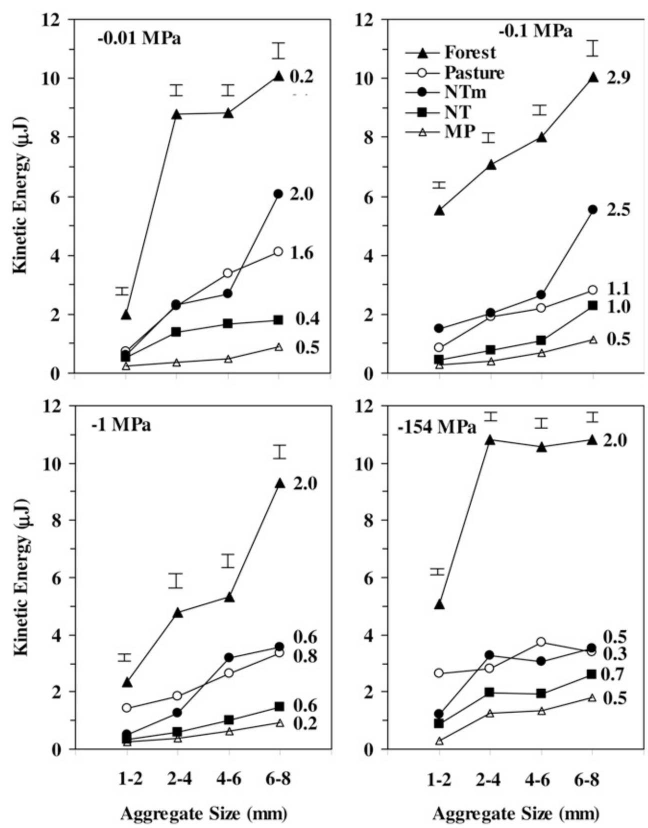

Fig. 1. Geometric mean kinetic energy of raindrops required to disintegrate soil aggregates by soil water potentials for moldboard plow (MP), no-till (NT), no-till with manure (NTm), pasture, and forest management for the 0- to 10-cm soil depth. The error bars are the LSD values comparing treatment effects within each aggregate size, whereas the numerical values are the LSDs comparing effects of aggregate size within each treatment.

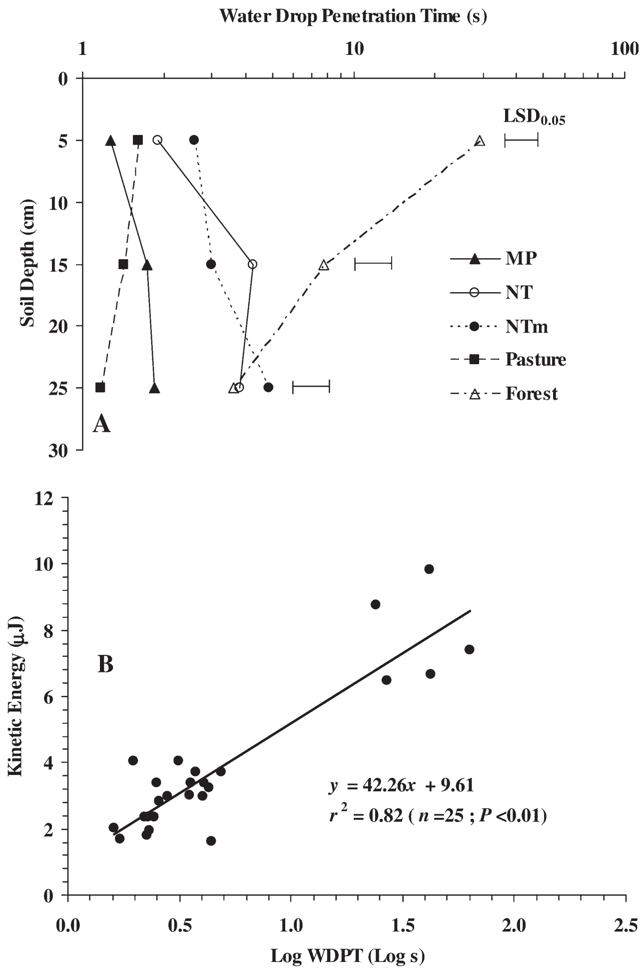

Fig. 2. (A) Mean water drop penetration time (WDPT) for moldboard plow (MP), no-till (NT), no-till with manure (NTm), pasture, and forest management, and (B) relationship of geometric mean kinetic energy of raindrops needed for aggregate disintegration with WDPT within the surface 0- to 10-cm soil depth.

software (SAS Institute, 2006). Differences among treatment means were tested using LSD for $P = 0.05$.

RESULTS AND DISCUSSION

Aggregate Disintegration

Geometric mean values of the KE of raindrops required to disintegrate soil aggregates by aggregate size under different soil water potentials are shown in Fig. 1. Treatment effects on the resistance of soil aggregates to the erosive energy of raindrops were large and highly significant ($P < 0.01$). Aggregates from forest soils required the highest (>5.0 μJ) KE for disintegration and those from MP soils the lowest (<1.9 μJ; Fig. 1). The differences in raindrop KE needed for aggregate disintegration between forest and agricultural practices were larger than those among agricultural practices. At the −0.01 MPa potential, the amount of raindrop KE required to disintegrate 6- to 8-mm aggregates was 10.11 μJ in forest, 6.07 μJ in NTm, 4.09 μJ in pasture, 1.80 μJ in NT, and 0.91 μJ in the MP treatment. Figure 1 shows that 2- to 8-mm aggregates from pasture and NTm required more raindrop energy for disintegration than those from NT and MP treatments.

Long-term management induced large changes in aggregate stability against raindrop impact. Aggregates from MP soils were structurally unstable and were dispersed readily by low raindrop energies, unlike those from other treatments. Intensive tillage in MP caused the breakdown of soil structure and loss of SOM, reducing the formation of stable aggregates (Blanco-Canqui et al., 2005). Conversely, abundant surface residue cover in long-term (>35 yr) NTm and NT management probably formed aggregates stable against slaking by producing organic binding agents in interaction with reduced soil disturbance (Tisdall and Oades, 1982). The high stability of aggregates in forest soils may be due to the large presence of decomposed SOM that acted as cementing agents, binding primary particles into strong aggregates (Chenu et al., 2000). The higher KE needed to disintegrate aggregates in the NTm compared with the NT treatment, particularly for the 6- to 8-mm aggregates from −0.01 to −1 MPa, indicated that manure addition had a significant impact on improving aggregate stability. Manure supplies organic binding agents and promotes microbial processes responsible for the enmeshment of soil particles into stable aggregates, particularly in long-term management systems (Pernes-Debuyser and Tessier, 2004). A study by Shukla et al. (2003) conducted on the same watersheds showed that manure addition increased aggregate size and improved aggregate stability where mean weight diameter of aggregates under long-term NTm was about two and three times higher than that under NT and MP, respectively.

The KE required to disintegrate aggregates increased with aggregate size. The increase in KE with aggregate size was larger for forest, pasture, and NTm than for MP, indicating that MP soils, because of the homogenizing and seasonal mixing of the plow layer, formed weak aggregates regardless of aggregate size. Six et al. (2000) observed that macroaggregates in NT soils are stable and have slow turnover rates due to the high content of fine particulate SOM, in contrast with those in plowed soils. The effects of soil water potential on the magnitude of aggregate disintegration were inconsistent and dependent on aggregate size. The KE decreased ($P < 0.05$) with an increase in moisture suction (more negative) for the >6-mm aggregates in NTm soils, suggesting that air-dry aggregates were more dispersible than moist aggregates in accord with the concept that rapid wetting of dry aggregates by rain causes a sudden release of the heat of wetting and the entrapped air, resulting in faster disintegration in contrast with moist aggregates (Collis-George and Lal, 1971). Because a large fraction of the pore space in air-dry aggregates was occupied by air, rapid aggregate wetting probably compressed the air inside the aggregates and caused sudden disintegration on internal pressure buildup, unlike moist aggregates, which reduced air porosity (Lado et al., 2004).

Aggregate Wettability

Data on WDPT were also lognormally distributed and the geometric mean WDPT for each management system by depth is shown in Fig. 2A. Soil aggregates had a very low water repellency (1 < WDPT < 10 s) for all treatments and depths except the forest soil at 0- to 10-cm depth. At this depth, mean WDPT was the highest (29.2 s) for forest soils and the lowest (1.2 s) for MP soils ($P < 0.01$). Despite the very low water repellency, however, values of WDPT among agricultural treatments differed significantly for all depths ($P < 0.01$). The WDPT for NT and NTm soils was 1.6 and 2.2 times higher, respectively, than that for MP for the 0- to 10-cm depth. The WDPT tended to increase with increasing depth for all but the forest soil, in which the WDPT decreased sharply with depth from 29.2 s for the 0- to 10-cm to 3.6 s for the 20- to 30-cm depth. The small but significant differences in WDPT among treatments persisted among depths, and NTm and NT treatments had consistently higher WDPT than MP and pasture.

Aggregates from forest soils reduced water entry more than those from agricultural practices, suggesting that aggregates from the forest soil would be more resistant to raindrop and runoff erosive forces. The WDPT for forest was 24.3 times higher than that for MP, 15.4 times higher than for NT, and 11.2 times higher than for NTM. These results are in accord with those of Chenu et al. (2000), in which the WDPT of forest soils was about six times that of soils cultivated for 7 yr and about 24 times that of soils cultivated for >35 yr in humic loamy soils. The presence of slowly decomposing forest litter, biological exudates, and particulate organic matter may explain the slower wetting of aggregates in forest soils (Ellerbrock et al., 2005). The specific organic compounds responsible for the retardation of water entry into aggregates in forest soils are, however, not well understood. Partly decomposed organic materials in association with microbial processes may have formed mucilaginous films on aggregate surfaces, partially obstructing pores, retarding the advance of the wetting front, and reducing air entrapment and rapid aggregate rupture in forest and manured soils. Chenu et al. (2000) observed that particulate SOM had hydrophobic characteristics and that SOM derived from crop residues was more wettable than that derived from forest or pasture. Determination of the composition and nature of the SOM of forest and agricultural soils is warranted to underpin the mechanisms responsible for the marked differences in wettability between forest and agricultural soils observed in this study.

The very low water repellency of agricultural soils in this study is in accord with the observations by Eynard et al. (2004), who observed that aggregates from MP, NT, and pasture treatments were all wettable (<5 s) across various soils in the Northern Great Plains. The results of our study differed, however, from those of Eynard et al. (2004) in that the WDPT differences among treatments, although small, were significantly different. The faster aggregate wetting in MP than in NT and NTm soils suggested that MP soils would slake more rapidly. Fast wetting causes air entrapment by preventing a uniform release of air from the aggregates (Eynard et al., 2004). Overall, long-term MP, NT, NTm, and pasture management systems did not have a large effect on water repellency compared with soils under forest.

Soil Aggregate Disintegration and Wettability vs. Soil Erosion

Aggregate disintegration was strongly correlated with the rate of aggregate wetting (Fig. 2B). Variations in log(WDPT) explained about 82% of the variability in KE values across treatments. These results suggested that aggregates that wet faster require less raindrop KE for their disintegration than those that wet slowly. Aggregates with slow wetting rates, such as those in forest soils, were more stable and resistant to raindrop impacts. Hence, the extent of soil erosion from forest soils would be significantly lower than that from agricultural soils. Aggregate disintegration based on raindrop KE was more responsive to management than aggregate wetting and was directly proportional to the magnitude of soil losses in accord with Shainberg et al. (2003). The correlations between raindrop KE and runoff and soil losses showed that runoff and soil loss decreased with the increase in raindrop KE required to disintegrate aggregates and log(WDPT) (Fig. 3). The MP soils requiring the lowest raindrop KE produced the highest amount of runoff and soil loss, whereas the pasture and NT treatments produced the lowest amount of runoff and soil loss, respectively. The higher disintegration in MP made the soil particles more transportable and probably increased runoff rates by surface sealing and reduced water infiltration (Rhoton et al., 2002). Indeed, Shukla et al. (2003) reported that cumulative infiltration under NTm (104 mm) and NT (87 mm) was significantly higher than that under MP (28 mm) in the same watersheds, attributed to the higher earthworm activity (Shipitalo and Butt, 1999; Blanco-Canqui et al., 2007) and lower bulk density and surface crusting (Blanco-Canqui et al., 2005) in NT systems. Although the raindrop KE required to disintegrate aggregates and WDPT in forest soils were much higher than in NT and pasture, differences in runoff and soil losses among forest, NT, and pasture treatments were small, suggesting that other factors (e.g., the amount and type of surface cover, earthworm activity) rather than raindrop KE and WDPT alone contributed to soil erosion in these watersheds.

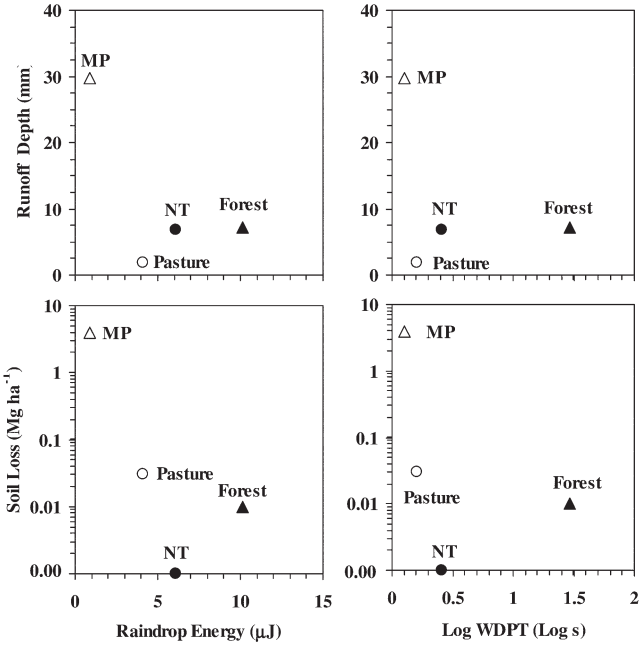

Fig. 3. Mean runoff depth and soil loss as a function of the kinetic energy of raindrops for aggregate disintegration and water drop penetration time (WDPT) for moldboard plow (MP), no-till without manure (NT), pasture, and forest management for the 0- to 10-cm soil depth. Because data on soil loss for the no-till with manure treatment were not available, this treatment was not included in the graph. Data on runoff and soil loss reported by Rhoton et al. (2002) and Jacinthe et al. (2004) were used in the study.

Relationships among Aggregate Properties

Management-induced changes in SOC concentration were the main determinants of differences in aggregate disintegration and WDPT among treatments. Figure 4 shows that WDPT and the raindrop KE required for aggregate disintegration were strongly correlated with changes in SOC concentrations across treatments ($P < 0.01$). The raindrop KE increased exponentially and log(WDPT) increased quadratically as the SOC concentration increased from 12.8 (MP) to 64.0 g kg^{-1} (forest). Changes

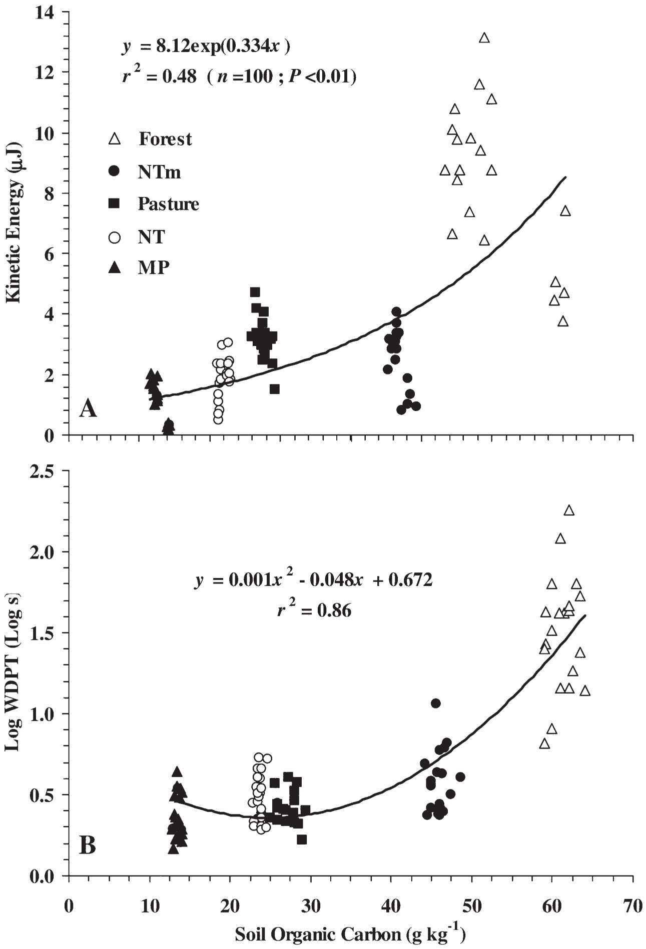

Fig. 4. Relationship of (A) geometric mean kinetic energy of raindrops needed for aggregate disintegration and (B) water drop penetration time (WDPT) with soil organic C concentration across the five treatments for the 6- to 8-mm aggregates within the surface 0- to 10-cm soil depth.

in SOC concentration explained about 48% of the variability in KE values and 86% in log(WDPT). A high raindrop KE was required to disintegrate aggregates that have higher SOC concentration and wet slowly. The SOM probably increased aggregate stability by increasing the cohesion of intraaggregate structure through the physical, chemical, and biological binding of soil particles (Tisdall and Oades, 1982) and by retarding aggregate wetting (Chenu et al., 2000). The SOC-enriched aggregates, such as from forest soils, were more stable and less wettable than those from cultivated soils. Manure-derived SOC combined with NT reduced aggregate disintegration relative to unmanured and plowed soils with low SOC concentration. The SOC increased the stability of soil aggregates and reduced breakdown under raindrop impact. The companion study by Blanco-Canqui et al. (2005) for the same watersheds reported that manured NT systems had higher SOC concentrations than tilled systems even at lower soil depths (30 cm), which was mainly attributed to the preferential leaching of soluble SOC compounds from the soil surface through the abundance of earthworm (*Lumbricus terrestris* L.) burrows (Shipitalo and Butt, 1999).

The KE needed to disintegrate aggregates was also significantly correlated with other aggregate physical properties such as ρ_{agg} and TS (P < 0.01; Fig. 5). The ρ_{agg} explained 84% of the variability in aggregate disintegration and 63% in log(WDPT), while the TS explained 47% of the variability in aggregate disintegration and 53% in log(WDPT). The inverse relationship of raindrop KE and WDPT with ρ_{agg} and TS suggest that aggregates with higher ρ_{agg} and TS were less wettable and stable. The dense and compact aggregates with low SOC concentration such as those in MP soils were easily dispersed by raindrops, whereas SOC-bound aggregates with low density such as in NT, NTm, pasture, and forest offered higher resistance to raindrop impact. Organic materials enmesh and glue soil particles while reducing aggregate density by "dilution" and increasing the stability of aggregates. Parker et al. (1995) observed that aggregate dispersion increased with increases in bulk density. Despite having higher ρ_{agg} and TS than NTm, NT, pasture, and forest (Blanco-Canqui et al., 2005), MP soils required less KE for the disintegration of aggregates, contrasting somewhat with the findings of some studies that reported that the amount of soil detached by raindrops decreases with increases in soil strength (Cruse et al., 2000). The higher values of ρ_{agg} and TS in aggregates under MP management are attributed to significant soil consolidation, as the soil samples were collected almost 1 yr after plowing. A similar study by Watts and Dexter (1997) on a silt loam reported that aggregates under intensively plowed soils had much higher ρ_{agg} and TS and lower SOC concentration and were more easily dispersed under rapid wetting than those from unplowed soils.

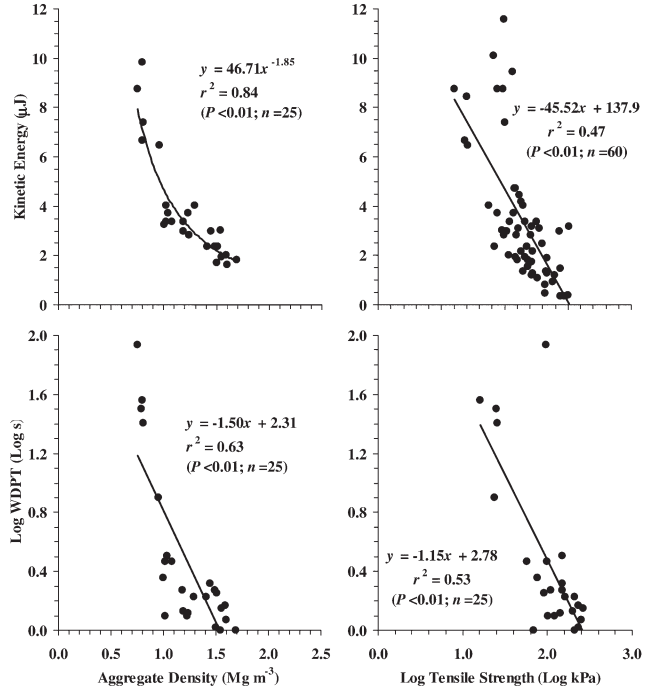

Fig. 5. Relationship of geometric mean kinetic energy of raindrops needed for aggregate disintegration and water drop penetration time (WDPT) with density and tensile strength for the 6- to 8-mm aggregates within the surface 0- to 10-cm soil depth.

The PTF for estimating aggregate disintegration was developed using WDPT, SOC concentration, ρ_{agg}, and TS as input parameters. The WDPT and SOC were the most sensitive predictors of the KE needed to disintegrate soil aggregates:

$$\text{KE of raindrops} = 9.46 + 29.67\text{WDPT} + 0.44\text{SOC}\ (r^2 = 0.79; P < 0.001)\quad [2]$$

where KE is expressed in microJoules, WDPT in seconds, and SOC in grams per kilogram. Equation [2] explained about 79%

of the variability of the KE requirements for aggregate breakdown. This site-specific PTF suggest that aggregate disintegration can be satisfactorily predicted using related soil aggregate parameters.

CONCLUSIONS

Long-term (>22 yr) land use and management systems altered aggregate disintegration in a Rayne silt loam in Ohio. Forest soils followed by pasture and NT management improved aggregate resistance to raindrops, whereas moldboard plowing formed weak aggregates that were easily detached by raindrops. Manure addition in interaction with NT management increased the aggregate resistance to raindrops compared with NT without manure. The effects of long-term agricultural practices on aggregate wettability were small, but the forest land use imparted some water repellency to the soil. The magnitude of aggregate disintegration was directly correlated with soil losses. Soils managed by MP had the lowest SOC concentration and aggregate stability and the highest ρ_{agg} and TS. Increases in SOC concentration significantly reduced the disintegration and wettability of aggregates. Changes in aggregate wettability and SOC concentrations are important predictors of aggregate disintegration using PTFs.

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